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The WIND-HAARP Experiment: Initial Results of High Power Radiowave Interactions with Space Plasmas

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13. ABSTRACT (Maximum 200 words)	
<p>Results from the first science experiment with the new HF Active Auroral Research Program (HAARP) facility in Alaska are reported. The initial experiments involved transmission of high frequency waves from HAARP to the NASA/WIND satellite. The objective was to investigate the effects of space plasmas on high power (~300 kW) radiowave transmission from the ground to high altitudes in the magnetosphere. The data acquired suggest that structured space plasmas along the propagation path impose a power law spectrum of intensity fluctuations on the transmitted waves, resembling that of scintillation interactions. However, because the transmitted wave frequencies are near ionospheric plasma frequencies, other types of wave-plasma interactions may occur. The measurements can provide an important new diagnostic tool for space plasmas.</p>	

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The WIND-HAARP Experiment: Initial Results of High Power Radiowave Interactions with Space Plasmas

1. Introduction

Most experimental diagnostics of space plasmas have been done with in situ measurements from satellites designed to orbit the earth in the regions of interest. These measurements provide detailed and spatially resolved measurements at single points, and information about large scale processes and dynamics has to be built up by statistical analysis of data sets acquired over an extended period of time. This approach tends to average out some of the time and spatial scales of dynamic phenomena.

Investigations of ionospheric and magnetospheric dynamics, with greater resolution in both space and time, are potentially possible with active probing at high frequencies (HF). The high latitude auroral region is known to have a wide range of scales of electron density structuring generated by various plasma instabilities [Keskinen and Ossakow, 1983]. Relatively strong density structuring is observed throughout the polar cap and auroral regions [Rodriguez and Szuszczewicz, 1984]. These density irregularities are typically magnetic field aligned structures that can extend for 100s of kilometers along the high latitude magnetic field and are convected across the polar cap by the large scale plasma convection. Many experimental and theoretical studies have shown that the density irregularities evolve with time and distance to produce a broad spectrum of density irregularities. Such structures are likely to be centers for scintillation and scattering of HF waves, as evidenced by the fading effects produced on communications links from satellites and from ground transmitters [Weber et al., 1986].

We report initial results from the use of ground-to-satellite transmissions of HF waves as a diagnostic for ionospheric plasmas. This experiment is an extension of the techniques used in ionospheric diagnostics with VHF incoherent and coherent scatter radars. Only a few experiments on scattering of HF waves from high altitude auroral structures have been attempted [Gurevich et al., 1992], and these have produced somewhat controversial results [Greenwald, 1994; Gurevich et al., 1994] or have indicated that greater detection sensitivity is necessary [Hysell et al., 1997]. One limitation of ground-based receivers is that, by being fixed on the ground, they are somewhat restricted in the range of viewing directions. With a satellite-borne receiver, however, it should be possible to sample a wider range of wave propagation angles rather quickly because of the motion of the satellite. Such experiments, however, require high power transmitters because the satellite receiving antenna is necessarily limited in its collecting area. Even so, there have been previous indications of wave scattering interactions in space plasmas [Alexander et al., 1979] that suggest that it is possible to detect and diagnose HF wave interactions.

2. The WIND-HAARP Experiment

We discuss below initial results from the WIND-HAARP experiment, the first science experiment using the new HAARP high power transmitter being constructed near Gakona, Alaska. HAARP is a combined Air Force/Navy project that will provide a state-of-the-art ionospheric diagnostic facility at auroral latitudes. The scientific objectives of the HAARP facility are described in the Internet Web site at <http://www.haarp.alaska.edu>. The HAARP antenna array is being constructed in steps, and the final 180-antenna configuration will provide effective radiated powers (ERP) up to 3.2 Gigawatt. The experimental measurements discussed below were acquired with HAARP in its initial engineering test configuration consisting of 16 crossed-dipole antennas and 32 transmitters, providing a total power of 300 kW and effective radiated power of about 10 Mwatts. The transmitting array is designed to be electronically steerable within 30° of the zenith, covering frequencies of transmission from 2.8 to 10 MHz. These transmitter frequencies are designed to cover the range of plasma frequencies of the high latitude ionosphere for "overdense" type experiments, i.e., where the ionospheric plasma frequency is greater than the transmitted frequency, so that reflection from the ionosphere occurs. However, these frequencies can also be used for "underdense" type experiments, in which the plasma frequency is less than the transmitted frequency and both forward and backward scattering of the HF wave can occur. Because the high latitude ionospheric electron density can be both very low and highly structured (especially at night), the possibility for several types of wave interactions exists. Space-based receivers, covering a wide range of spatial distances and scattering angles, will allow new investigations of these interactions. Deriving an understanding of HF wave interactions at high latitudes can also lead to greater understanding of the dynamics of this region of the magnetosphere.

The extent to which such HF radiowaves launched from HAARP will scatter from high altitude magnetospheric density irregularities and gradients is not well known, although theoretical studies and the experiments referred to above suggest that the scattering cross section is likely to be low. An experimental check at a variety of scattering angles has not been possible before because of geometric constraints on transmitting and receiving facilities. With the HAARP research facility now coming online, the WAVES radio receiver on the NASA/WIND spacecraft can provide a space-based receiving point for ground-launched radiowaves. This combination of HF transmitter and satellite receiver has not been available before; WIND is one of only a few operational satellites available for this type of experiment.

The WIND satellite was used to receive transmissions from HAARP in several different campaigns beginning in November, 1996. The WAVES RAD2 receiver, which was designed to observe solar radio bursts [Bougeret et al., 1995], is fortunately well suited to observe HF transmissions from HAARP also, and various new instrument modes have been developed to allow maximum data rates for acquisition of the HAARP transmissions. The RAD2 receiver is a stepped frequency receiver covering 256 frequencies from 1.075 MHz to 13.825 MHz, in 50-KHz intervals, with 20-KHz bandwidth, and a detection threshold of ~ 7 nVolt/ $\sqrt{\text{Hz}}$. The time

interval for the receiver to step through 256 frequencies is 16.192 seconds, with the effective dwell time per frequency being about 60 ms. The detection is done with a 15-meter length dipole (S) in the spin plane of the satellite and an 11-meter length dipole (Z) perpendicular to the spin plane. The S-antenna rotates with the spacecraft at a 3-sec period while the Z-antenna has no effective rotation because it is aligned with the spin axis. The orbit of WIND provides the sampling at a wide range of radial distances from the earth, from $10 R_e$ to $250 R_e$, where R_e is in units of earth radii. Some initial observations of the WAVES experiment and are reported in Kaiser et al., [1996].

3. Experimental Plans

The WIND-HAARP experiments were conducted during the fall and early winter of 1996, when the WIND spacecraft was in close orbit about the earth. WIND is normally kept near the L1 libration point, about $250 R_e$ upstream of the earth, where it has provided long term monitoring of the solar wind. However, semi-periodically, the spacecraft is brought back near the earth for lunar flybys that provide station-keeping orbit adjustments. During these phases, the spacecraft is within $10-40 R_e$ of the earth and in a relatively good position to receive HF transmissions from HAARP. Figure 1 shows the orbit trajectory predicted for WIND during the period 16-18 November 1996, in earth-centered solar ecliptic coordinates. The particular phase of the WIND orbit shown in Figure 1 was one of several for which the initial WIND-HAARP experiments were planned during the November-December 1996 period. Although the orbit of WIND is in the same plane as the moon, the tilt of the earth's rotational axis in the fall and winter allows WIND to appear at elevations as high as 50° as seen from the high latitude HAARP site. The times of optimum elevations occurred at early to late morning local times. The experiments were done at times when WIND was above about 35° elevation, at southward azimuth angles of $165^\circ-185^\circ$. However, WIND was still offset from the HAARP main lobe maximum and the experiments must relied on sidelobe transmission. The HAARP transmitted waves thus passed through ionospheric and magnetospheric plasmas southward, rather than directly overhead of the HAARP site. In Figure 1, we list the start and stop times of four selected experiment intervals. Figure 1 also shows plots of models of the plasmapause, magnetopause, and bow shock, to provide a geometric perspective of the spatial scale of the experiments. As part of the experiment campaign, the Russian Sura HF radar also participated on one experiment. In this report, we discuss results only from the first HAARP experiment, conducted on 16 November 1996 at Universal Times (UT) of 1330 to 1630. For the hourly intervals of the HAARP transmissions, the WAVES RAD2 receiver was switched from its normal 256-frequency stepping mode to sample only the transmitted frequency at maximum rate, corresponding to 0.06325 sec between samples. The field strengths measured with the Z-antenna of WAVES are the data discussed below. The Z-antenna does not impose a spin-modulation on the received signals and thus avoids an extraneous source of amplitude variation. For this first experiment, WIND was at radial distances of 18 to $20 R_e$, near the expected location of the morningside magnetopause.

In planning the WIND-HAARP experiments, we evaluated the maximum expected power densities of HF waves at the WIND spacecraft, assuming free-space propagation from the transmitter to the WAVES receiver. In Figure 2, we show the field strength at WIND according to radiated power levels from the HAARP transmitting array. Each curve corresponds to a level of ERP, in terms of dB above 1 watt, that is either currently available or planned for HAARP. The variation of radiated amplitude shown is that due to r^{-2} dependence only and in the maximum of the main lobe of the HAARP antenna array. Thus, the curves give the maximum field strength that WAVES would receive. For the experiments discussed in this report, the HAARP-radiated power level corresponded to about 10 Mwatts ERP, and the maximum field strengths at WIND radial distances are shown in the shaded polygon on the plot. However, for the elevation angles of WIND the radiated power would be from the antenna sidelobes, and the received field strengths would be lower. The detection threshold for the WAVES receiver is indicated by an arrow.

4. Experimental Results

The first frequency planned for transmission from HAARP was 4575 KHz, between UT 1330 and 1430 on 16 November. However, this transmission did not occur. In the second hour of the experiment, UT 1430 to 1530, HAARP radiated 7575 KHz, in the Ordinary (O) polarization mode at 300 kW full power (ERP \sim 10 MW). In the third hour, between UT 1530 and 1630, HAARP radiated 9075 KHz at 300 kW, also in O-mode. In order to provide a recognizable signature, it was planned that the HAARP transmissions would be amplitude modulated ON and OFF with 30-sec period in the first and last 5-minute intervals of each transmitted frequency. Continuous wave (CW) transmission occurred at all other times. The HAARP-transmitted frequencies were also selected to be in parts of the HF spectrum that are usually clear of noise from other sources. For this selection, we examined previous measurements of the HF spectrum as obtained by the WAVES instrument at similar radial distances from earth.

In Figure 3, we show plots of the signal amplitudes received at WIND during the first 10 minutes of each of the HAARP transmissions between UT 1430-1530 and UT 1530-1630. The wave amplitudes ΔV are in calibrated voltage spectral density (μ volts/ $\sqrt{\text{Hz}}$). Below each data plot is a profile of the transmitter power modulation, showing the 30-sec ON-OFF modulation in the first 5 minutes followed by CW transmission. In the upper panel, corresponding to transmission at 7575 KHz, a careful examination of the data and correlation with the transmission modulation shows that the 30-sec ON-OFF modulation is present, thus confirming that the received waves are the HAARP transmissions. The ON-OFF modulation is clearly evident for the 9075 KHz transmission in the lower panel. The most obvious result of the initial WIND-HAARP experiment is that the transmitted waves are received with considerable signal amplitude fluctuations. Such amplitude fluctuations are seen throughout the two hours of the transmissions at 7575 KHz and 9075 KHz and clearly suggest that the HF radiowaves are interacting with space plasma irregularities along the propagation path. The overall amplitude levels of the received waves are seen to be smaller by about an order of magnitude or more compared with the plots of Figure 2. The lower amplitudes are primarily due to WIND being in the sidelobes of the

transmitting antennas, as discussed above. However, it is also apparent that the 7575 KHz waves are at lower amplitude than the 9075 KHz waves, although both frequencies were transmitted at the same power levels, and the antenna lobe patterns are essentially the same at both frequencies. The OFF periods of the transmissions provide a measure of the noise background and show that at 7575 KHz the signal amplitudes are at least a few times larger than the noise background. At 9075 KHz a much quieter background is detected, and the signals are about an order of magnitude greater than background. The ON-OFF modulations of the final 5 minutes of each hour exhibit somewhat quieter noise levels than those shown in Figure 3, so that the background noise levels appeared to decrease during the experiment.

In Figure 4, we have selected 1024 data points (about 1 minute) from the CW portion of the HAARP transmissions to analyze with Fast Fourier Transform (FFT) techniques. The upper panel shows the spectrum of intensity fluctuations at 7575 KHz over fluctuation frequencies of 0.015 Hz to 7.9 Hz for the time UT 1436 to 1437. The highest frequency in the spectrum is determined by the Nyquist frequency associated with the sample rate of the data. A least-squares fit to the power law $S(f) = S_0 f^m$, where S is the spectral intensity ($\mu\text{volts}^2/\text{Hz}$) and f is the fluctuation frequency (Hz), gives spectral index $m = -2.06$. For the same time interval the scintillation index $S4 = 1.23$. The scintillation index is defined by $S4 = \text{std}(I)/\text{mean}(I)$, where $\text{std}(I)$ is the standard deviation of the wave intensity and $\text{mean}(I)$ is the mean of the wave intensity, and $I = (\Delta V)^2$. A similar spectrum for waves received at 9075 KHz for UT 1536 to 1537 is shown in the lower panel, with spectral index $m = -2.65$ and $S4 = 0.855$. These spectra are similar to the scintillation spectra induced by high power HF transmitters that are discussed in Basu et al., [1997]. However, in the latter case, the spectra are observed by ground-based receivers of 250 MHz beacons on quasi-stationary spacecraft in Molniya orbit.

Dynamic spectra of the intensity fluctuations of the 7575 KHz and 9075 kHz transmissions are shown in Figure 5. In these plots, the fluctuation intensities are gray-scale coded with fluctuation frequency along the vertical axis and Universal Time along the horizontal axis. Such dynamic spectra can reveal time-dependent spectral details that may not be evident in individual plots like those in Figure 4. The dynamic spectra are derived by FFT techniques; however, in this case, we have used data points in 256-point intervals to compute each dynamic spectrum. Each succeeding spectrum is computed by advancing the 256-point window forward by 64 points. Thus, each succeeding spectrum involves a 64-point overlap. This technique provides a smoothing and filling function that helps to enhance spectral details. The dynamic spectra are consistent with the power law spectra of Figure 4, with greatest power at lowest frequencies and generally dropping off toward the highest frequency of about 8 Hz. In the interval of CW transmission, the dynamic spectra are generally composed of irregular intervals of signal enhancements and decreases across the entire range of fluctuation frequencies. In terms of the spectra in Figure 4, these variations correspond to broadband intensity variations that maintain approximately the same power law dependence.

The upper panel of Figure 5 corresponds to the 7575 KHz transmission. In the initial 5-minute interval of ON-OFF modulations (UT 1430 to 1435), only one 30-sec ON period is apparent. The initial ON-OFF modulations are more apparent in the top panel of Figure 3. However, the OFF intervals of Figure 3 indicate that the background noise is almost comparable to the received signal at 7575 KHz, thus making the initial ON-OFF modulations less evident in the dynamic spectrum. In the final 5-minute interval (UT 1525 to 1530), because of operational problems, only one 30-sec ON-OFF modulation was possible, but this one ON interval is seen clearly. Transmission remained in the OFF state until UT 1530, so that a relatively quiet background at 7575 kHz was measured in the interval UT 1528 to 1530. Thus, it appears that the background noise level at 7575 KHz decreased between UT 1430 and 1530. The dynamic spectrum also suggests that a weak feature at about 2.1 Hz is detected between UT 1435 to 1525.

In the lower panel of Figure 5, we show the dynamic spectrum of the intensity fluctuations of the 9075 KHz transmission, which began immediately after the 7575 KHz transmission ended. The dynamic spectrum for 9075 KHz is consistent with a power law. Also, the wave amplitudes for 9075 KHz are higher than those for 7575 KHz, the ON-OFF modulations are clearly seen at the beginning and end of the one-hour interval, and lower background levels occur during the OFF periods. The dynamic spectrum also indicates numerous burst enhancements of the spectral density during the interval of CW transmission, UT 1535 to 1625. A narrow "line" enhancement at a frequency of about 2.7 Hz is also detected throughout most of the one-hour transmission interval. This feature appears to vary in intensity approximately with the broadband intensity of the spectrum. The source of this spectral line may be similar to the weak feature seen at 2.1 Hz in the upper panel. At UT 1630, the HAARP transmission ended and only background noise was measured thereafter by the WAVES RAD2 receiver.

In order to obtain a general view of the spectral intensity fluctuations observed at 7575 KHz and 9075 KHz, we have calculated the variations of the spectral index m and the scintillation index $S4$ throughout each hour of the transmissions. These values are plotted in Figure 6 and were obtained for the same 256-point intervals used to calculate the dynamic spectra in Figure 5. In the panels of Figure 6 the scale for $S4$ is shown on the left and the scale for m is shown on the right of the plots. In the upper panel, the interval of CW 7575 KHz transmission leads to $S4$ variations between 0.5 and 1.0 primarily, with occasional large values. The spectral index m at 7575 KHz generally averages about -2.2. For the CW 9075 KHz transmission, shown in the lower panel, $S4$ is also found in the range 0.5-1.0, while the spectral index m averages about -2.4 and varies over a slightly wider range. The large variations during the ON-OFF modulation intervals are an artifact due to the inclusion of zero-level signal values in the calculation of the two indexes. For each of the transmitted frequencies we list in Table 1 the mean values and standard deviations of $S4$ and m , based on values calculated during the intervals of CW transmission only.

5. Summary and Conclusions

The WIND-HAARP experiment is one of a series of experiments utilizing high power HF transmitters on the ground in conjunction with spacebased receivers. The first experiment shows that the HAARP facility can provide an important new approach to the study of space plasmas. The measurements show that irregularities in the ionized medium between the transmitter and receiver impose amplitude fluctuations on the waves with power law spectral signature. Because the transmitted frequency is close to the maximum plasma frequency of the ionized medium, stronger wave-plasma interactions involving both phase and amplitude may occur. Thus, the irregularities causing scintillation may be a combination of naturally occurring ionospheric structures and structures artificially induced by the high power transmissions. The statistical values in Table 1 show that the observed power law spectra correspond to strong scintillation, with average values of $S4 \sim 0.8$ to 0.9 and spectral slopes in the range -2.2 to -2.4. Although both 7575 KHz and 9075 KHz transmissions were done at the same power levels, the 7575 KHz transmission has less power at the WIND satellite. It is likely that stronger scattering and/or absorptive interactions occur for 7575 KHz because this frequency was closer to the critical plasma frequency of the ionosphere. Ionosonde measurements were not available for this experiment; however, the value of the critical frequency f_c may be estimated from the observations. For example, if we assume that 7575 KHz was just able to penetrate the ionosphere at a zenith angle of 55° , the overhead critical frequency would have to be no greater than about $f_c = 7575 \cos(55^\circ) = 4345$ KHz. This value is consistent with the latitude of the HAARP facility and the early morning local time (0530 to 0730) of the experiment. The source of the features at 2.1 and 2.7 Hz in the dynamic spectra of Figure 5 is presently not known. A low-level modulation of the HAARP transmitters may be the source, or perhaps some wave-plasma interaction. It is interesting to consider that the ratio $(2.7 \text{ Hz})/(2.1 \text{ Hz}) \sim 1.3$ is close to the inverse ratio of the corresponding transmission wavelengths $(39.58 \text{ m})/(33.04 \text{ m}) \sim 1.2$, suggesting some interaction with plasmas having structure at multiples of the transmitted wavelengths. From a study of such spectral details, new diagnostic capabilities may be developed. It is also likely that most of the broadband fluctuations observed for the transmitted waves occurred in the ionosphere. However, because the WIND spacecraft was at large radial distances, it is conceivable that wave interactions may also occur at magnetospheric boundaries with significant density gradients, such as the plasmapause, magnetopause, or bow shock. In such cases, the use of powerful ground-based transmitters may provide a new approach to the study of magnetospheric boundary dynamics.

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Table 1. Mean values and standard deviations (std) of S4 and m (intervals of CW transmission only)

Frequency (KHz)	
7575	9075
S4 mean.....	0.75
S4 std.....	0.19
m mean.....	-2.2
m std.....	0.26
Number of values used.....	725
	725

Figure Captions

Figure 1. Trajectory of WIND spacecraft in earth-centered solar ecliptic coordinates for the period 16-18 November 1996. Experiment numbers along the trajectory correspond to the Universal Time intervals listed; tick marks are at hourly intervals. The arrows indicate the propagation directions from the transmitter to the spacecraft for each experiment. The dashed lines indicate the ecliptic plane geometries of the plasmapause, magnetopause, and bow shock. The experiments occurred at early to late morning local times of the transmitter sites.

Figure 2. Main lobe field strengths as a function of (radial distance)⁻² of WIND from the HAARP transmitter. Each curve corresponds to a change in radiated power by 5 dBW. The shaded polygon indicates the range of field strengths for the radial distances (18-40 R_e) of WIND on 16-18 November 1996. The WAVES receiver threshold for detection is indicated by the arrow.

Figure 3. Measured amplitudes at WIND of the HAARP transmissions on 16 November at 7575 and 9075 KHz. Below each data plot is shown the pattern of 30-sec ON-OFF transmission, followed by continuous ON transmission. The ON-OFF modulation pattern allows identification of the HAARP transmission. The highly variable signal strengths are observed throughout the entire transmission.

Figure 4. Signal fluctuation spectra for approximately 1-minute intervals of the 7575 and 9075 KHz transmissions in Figure 3. The spectra are fitted by power laws with spectral indexes m of -2.06 and -2.65.

Figure 5. Dynamic spectra of 7575 KHz and 9075 KHz transmissions from HAARP in the interval UT 1430 to 1630. The spectral intensity of signal fluctuations is gray-scale coded. The burst appearance of the spectra indicate the large signal fluctuations shown in Figure 3. Weak features at about 2.1 Hz and 2.7 Hz are seen in CW intervals of 7575 KHz and 9075 KHz transmissions, respectively.

Figure 6. Variation of the scintillation index S4 and spectral index m of the 7575 KHz and 9075 KHz transmissions. The S4 variation is indicated by the solid line plot, and the m variation is shown by the solid line plot with dots. For both transmitted frequencies, the values correspond to strong scintillations.

WIND Ecliptic Plane Trajectory
16-18 November 1996

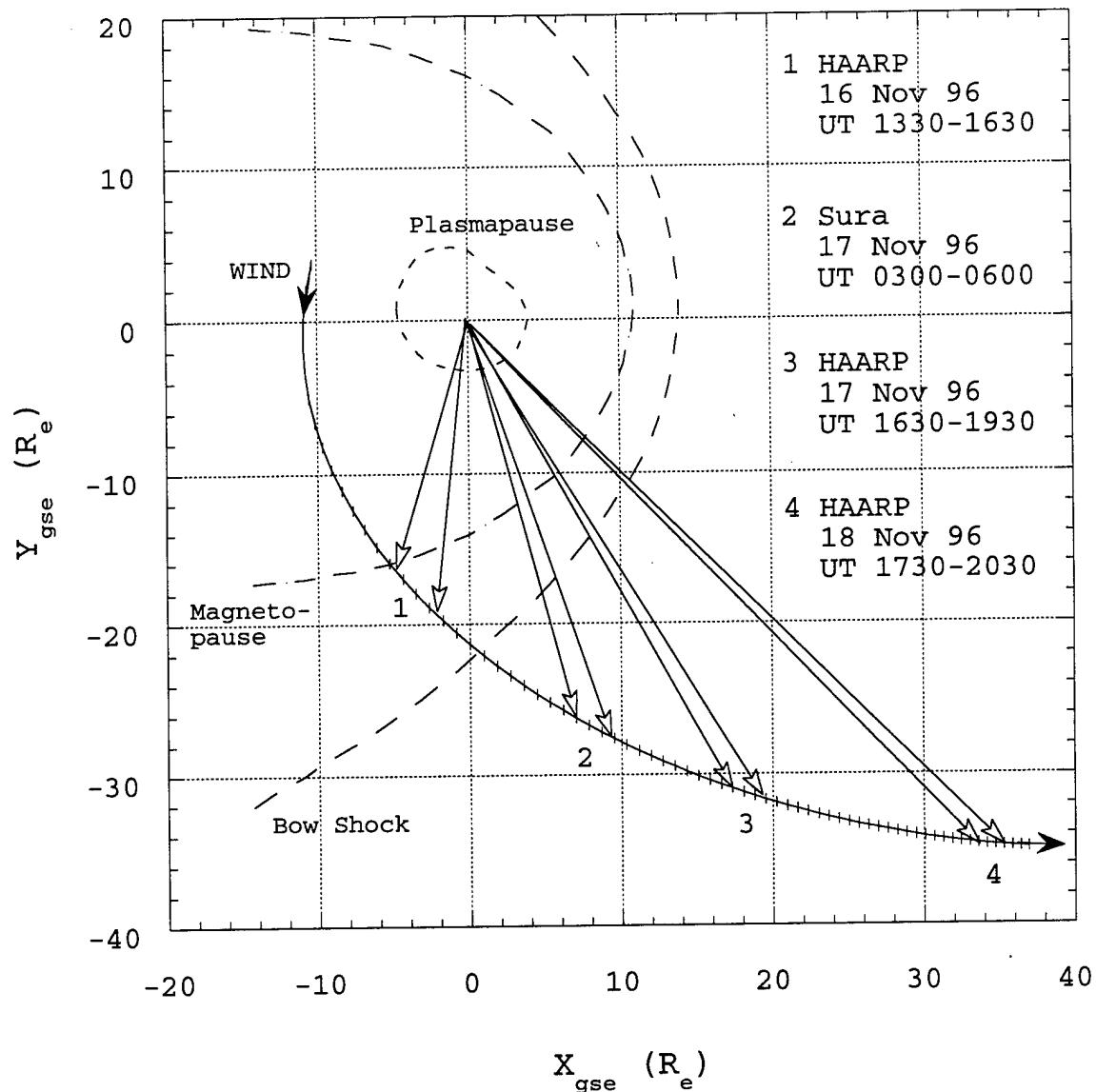


Figure 1.

HAARP Radiated Field Strength

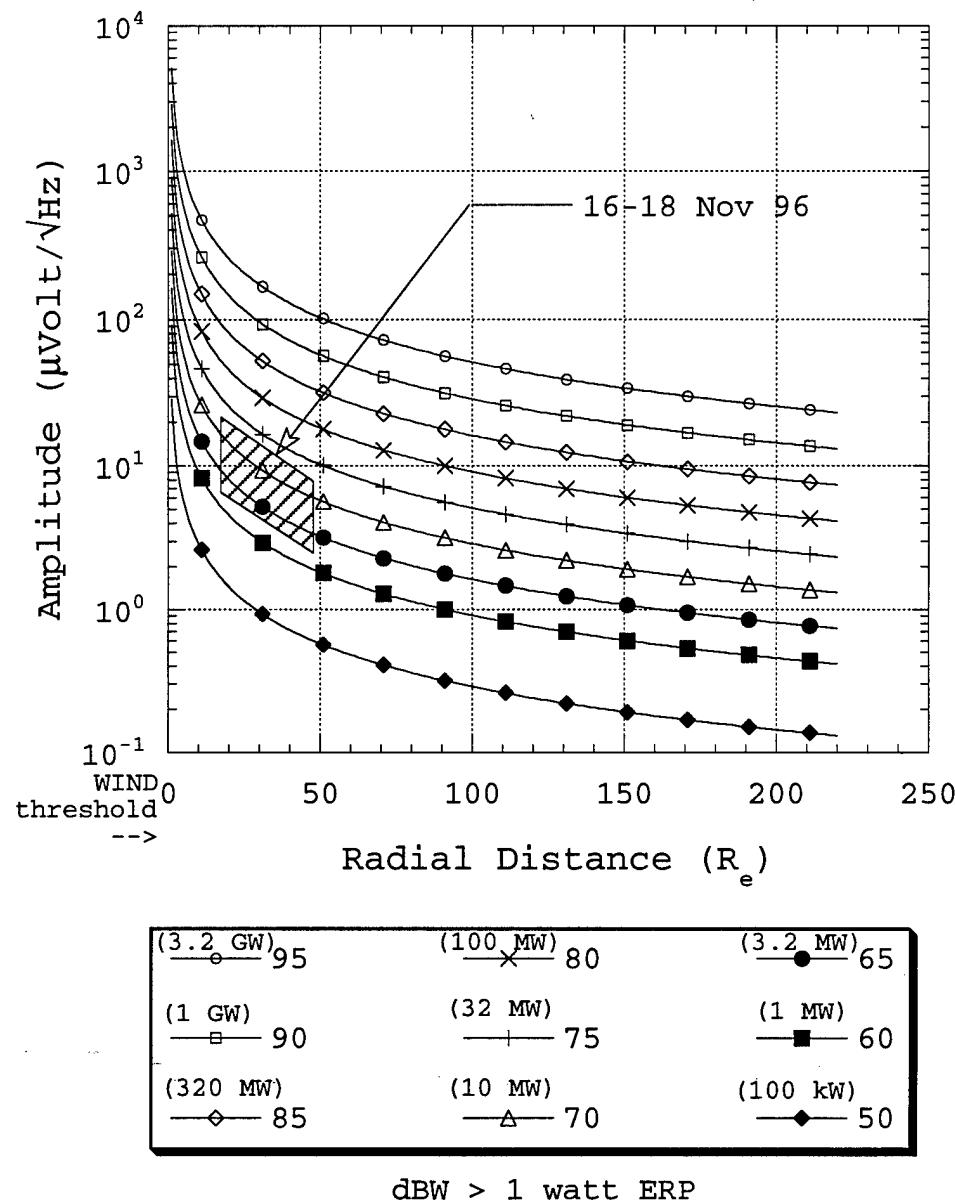
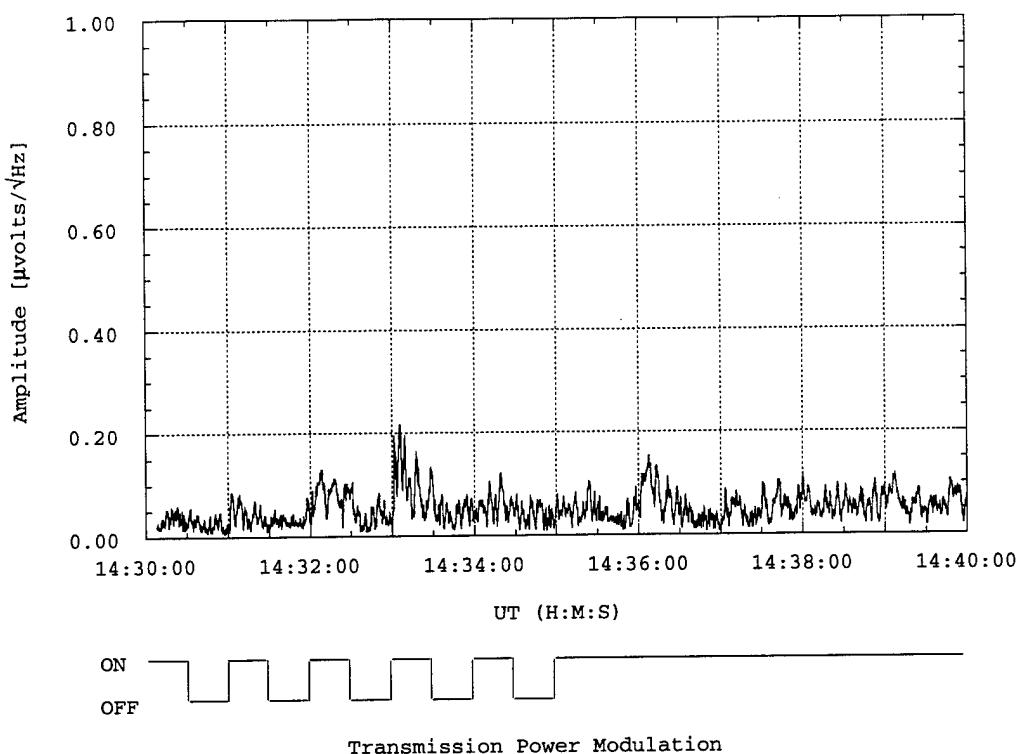


Figure 2.

WIND-HAARP 16 Nov 96 7575 kHz



WIND-HAARP 16 Nov 96 9075 kHz

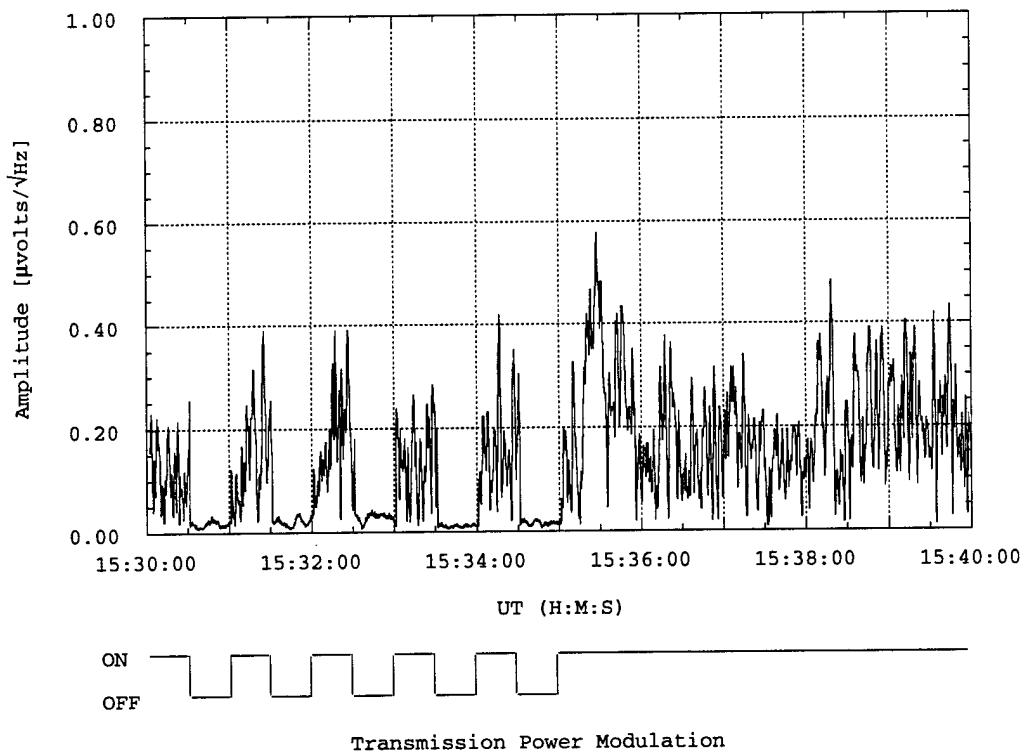
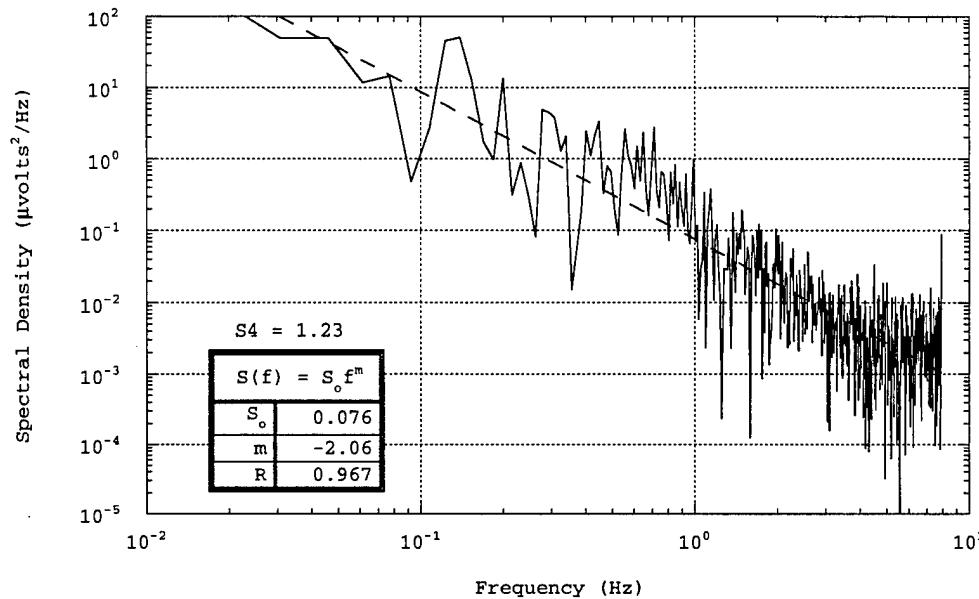


Figure 3

HAARP 7575 kHz 16 Nov 96 UT 1436-1437



HAARP 9075 kHz 16 Nov 96 UT 1536-1537

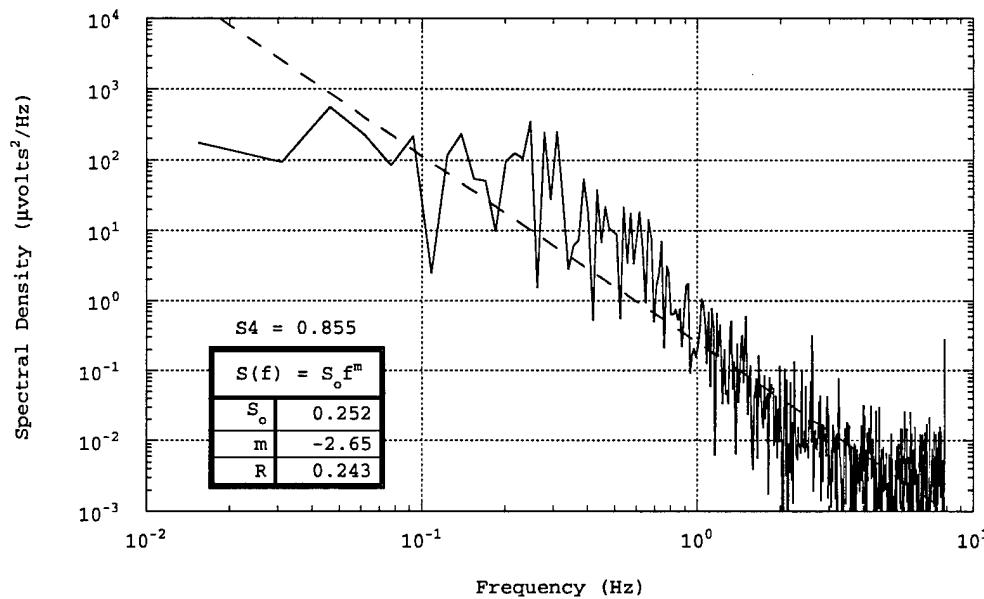


Figure 4

WIND-HAARP 16 November 1996 7575 kHz

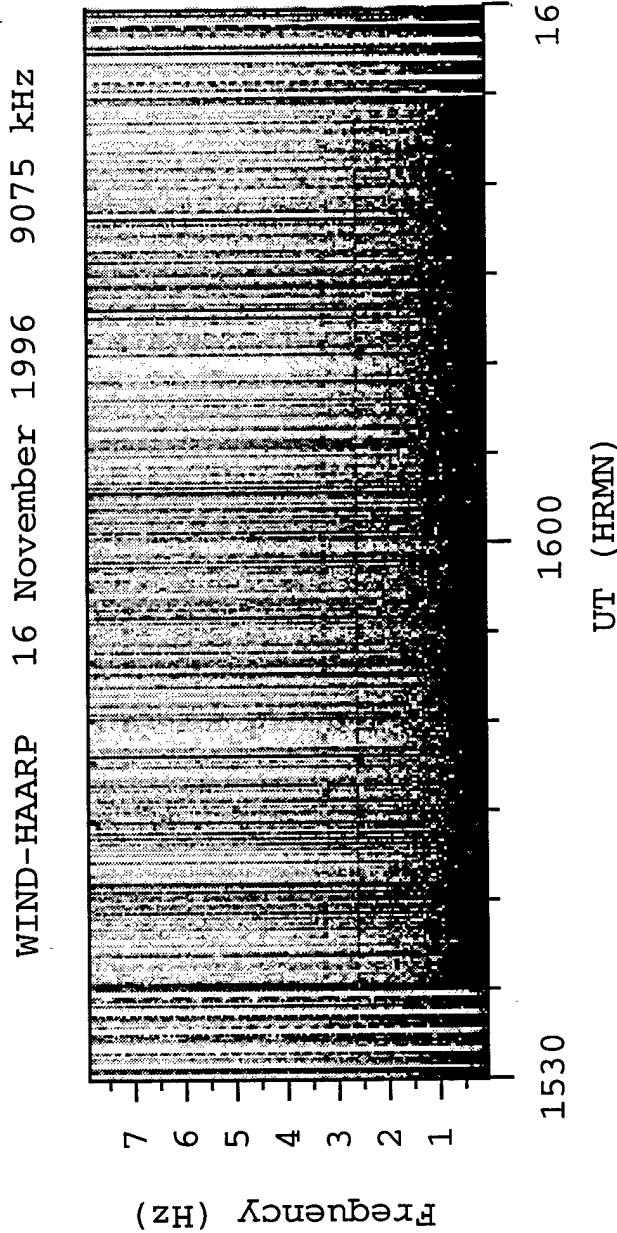
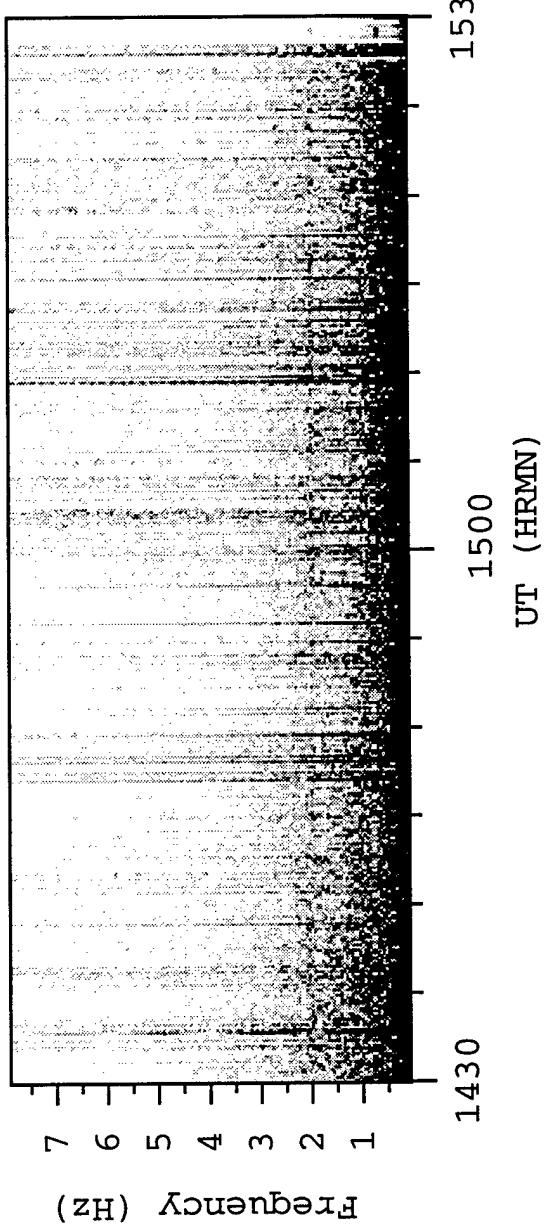
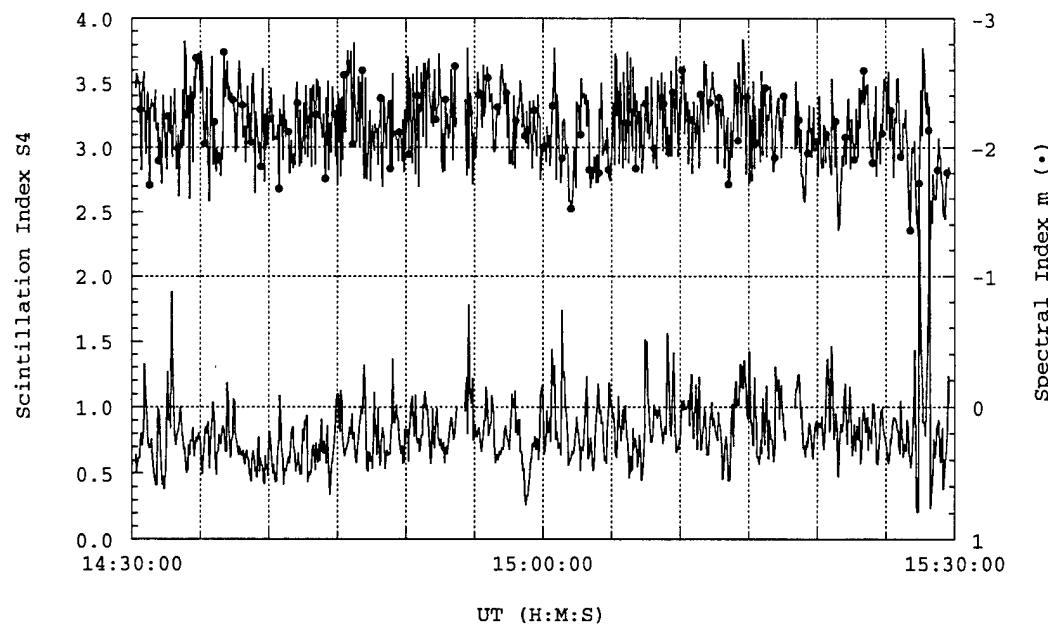


Figure 5

WIND-HAARP 16 Nov 96 7575 kHz



WIND-HAARP 16 Nov 96 9075 kHz

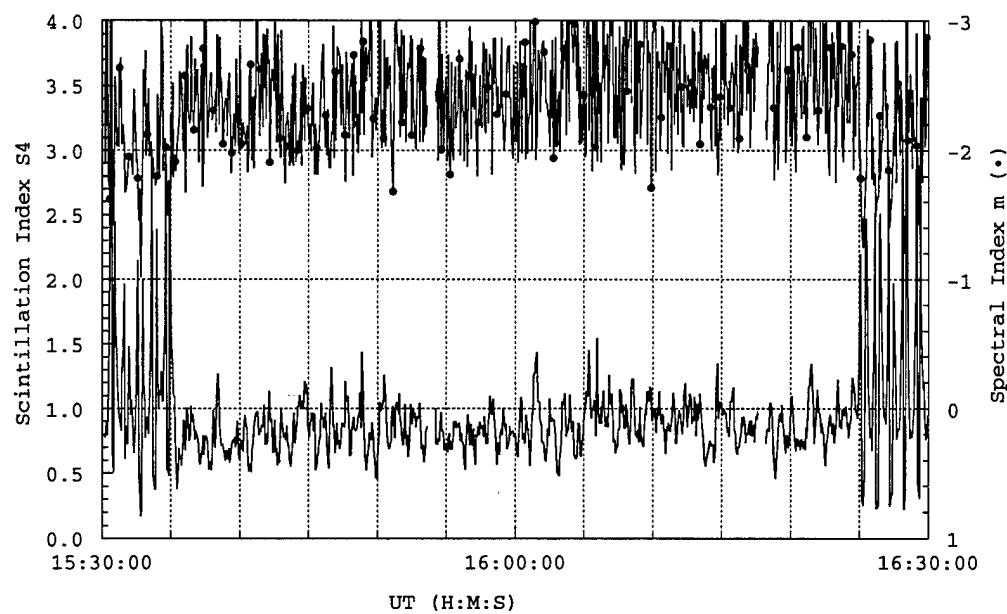


Figure 6